Energize Missouri: Algae-Based Renewable Energy Study

Task A
Potential of Algae-Based Biofuels to Meet the Energy Needs of Missouri and the United States

Final Report

For
Missouri Technology Corporation

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For
Missouri Technology Corporation
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Jefferson City, Missouri 65102

Attn: Jason Hall

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Preface

This report was prepared for the Missouri Technology Corporation under a subgrant award to MRIGlobal and entitled “Energize Missouri: Algae-Based Renewable Energy Study” signed by Mr. Jason Hall and dated February 28, 2011. Work was initiated in accordance with a work plan submitted and approved on March 11, 2011. The project team includes members from MRIGlobal, Washington University in Saint Louis, and the University of Missouri, Columbia.

The objective of the grant is to produce a study to help define the development and commercialization of algae as a fuel source that would be a valuable adjunct to the state energy plan. The study would emphasize the potential benefits to the state economy that a commercial algae industry could bring, opportunities for Missouri to become a leader in such an industry, and the policy steps and collaborations that the state could initiate to strengthen Missouri’s leadership in this area. The study is divided into seven tasks plus a final report. This report is the results of Task A which sought to assess in broad terms the potential for algae-based biofuel to help meet the energy needs of Missouri and the United States. As such, it sets the stage for more detailed analysis that will be conducted and reported out in the subsequent tasks.

This Task A study was authored by Jay Turner of Washington University in St. Louis (WUSTL) as Principal Investigator and co-authored by John Murphy (WUSTL). The authors wish to acknowledge contributions by Bill Babiuch, Stanley Bull, Gregory Karr, and Thomas Grant (MRIGlobal). We also gratefully acknowledge conversations with Richard Sayre (Donald Danforth Plant Science Center), Tom Verry and Shelby Neal (National Biodiesel Board), and Richard Axelbaum, Robert Blankenship, Raymond Ehrhard, Mark Henson, and Himadri Pakrasi (WUSTL).

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Section 1. Introduction

1.1 Study Motivation and Scope

Petroleum has been the fuel source of choice for U.S. transportation needs since the gasoline internal combustion engine achieved dominance in the 1910s. In 2009, petroleum accounted for 94 percent of U.S. transportation fuels and 38 percent of the overall U.S. energy consumption (U.S. EIA, 2010a), yet there are several significant concerns over our continued reliance on it. Domestic oil production peaked in the 1960s and continues to decline; currently 70 percent of the petroleum in the domestic energy supply is imported. While about half of the imported oil comes from the Western Hemisphere, nearly 40 percent comes from the Persian Gulf and Africa with both supply and prices subject to geopolitically-driven instabilities. Our current reliance on petroleum from foreign sources is generally considered to be unsustainable and indeed the U.S. Energy Information Agency (EIA) projects that over the next 25 years policies to promote domestic fuels production will decrease exports to account for about 45 percent of domestic fuel oil consumption although demand will continue to rise (U.S. EIA, 2010b).

There are additional stresses on the global petroleum supply. The U.S. accounts for about 20 percent of the global energy consumption but the economies are rapidly growing in several counties, especially China, and the increased demand will likely lead to increased prices. A worldwide economic downturn caused a drop in oil prices from 2008 to 2010, but the upward price rise that was evident throughout the early 2000s has resumed in 2011 with an improving economy. The petroleum market is large and complex which leads to uncertain price projections. However, many forecasters project domestic petroleum prices to increase at rates equal to or faster than inflation (CEC, 2011). Environmental concerns over fossil fuel production (mines, wells, etc.) and use are also routinely in the spotlight. Several states have responded to this and other concerns about conventional fuel sources by adopting requirements that specify a percentage of the electricity supply be provided by renewable or alternative energy sources (Pew Center, 2011). In this case, however, the focus tends to be on broadening the energy portfolio for electricity generation rather than transportation fuels.

In light of the economic, supply security, and environmental stressors that come with our reliance on petroleum—especially imported—the search is on for fuel oil alternatives to petroleum. Various agricultural crops, most notably soybeans and corn within the U.S., are being used to produce alternative fuels such as biodiesel and bioethanol, respectively. One of the more provocative alternatives is biofuels produced from algae. This concept is not new—the U.S. Department of Energy (DOE) has funded research in this area since the first oil crisis in the 1970s.

Algal production of biofuels requires a unique blend of expertise from various technical fields including biology, chemistry, and engineering. Algal biofuel production is technically feasible but faces economic and logistical challenges. Outdoor (open pond) production requires adequate land, abundant supplies of water and nutrients, and an acceptable climate. These resource demands tilt the playing field to favor certain geographic locations but comparative siting assessments are few and limited in scope. Downstream processing of the algae to make biofuels is also equipment and energy intensive. A vast number of producers, processors, equipment suppliers and other service providers are needed if algal-based biofuels are to replace a significant portion of petroleum-based fuels. Given its geography and resources, the State of Missouri may have locations within its borders suitable for algae production and processing. Further, Missouri's strong industrial and agricultural base could be great assets for the growth of equipment suppliers and services to support this nascent industry. Given the importance of transportation fuels to the nation's economy, the economic and employment payoffs could be substantial.

The aim of this study is to evaluate the potential for Missouri to serve as a center for various aspects of the algal biofuel production enterprise. The tasks are as follows:

A. Assess the potential for algal biofuels to help meet the energy needs of Missouri and the United States.
B. Identify and document Missouri's algal biofuels research, resource, and industrial assets.
C. Compare Missouri's algal biofuels research, resource, and industrial assets to those of other states and countries to examine Missouri's competitive advantages, and to identify areas where greater efforts are needed.
D. Identify opportunities for Missouri to be a leader in supplying products and services to implement commercially viable production systems for algal biofuels.
E. Identify technical, regulatory, and fiscal challenges that prevent or hinder broad implementation of algal biofuels production systems.
F. Recommend strategic policy initiatives that Missouri could pursue to advance the large-scale implementation of algal biofuels systems.
G. Identify and recommend opportunities for Missouri to collaborate with other states and countries that have algal research, commercialization, and production expertise.

This first report for Task A presents in broad terms the motivation and potential for algal biofuel production for the U.S. in general and Missouri in particular. It serves as a primer on the overall enterprise with the subsequent six tasks providing more detailed analysis and reporting on each of the topics.

1.2 The Algal Biofuels Enterprise

Algae have been receiving considerable attention as a source of biofuels. In 2010 the DOE published the National Algal Biofuels Technology Roadmap which provides information from scientific, economic and policy perspectives concerning algal biofuels production and summarizes the current status of algal biofuel systems research and development (U.S. DOE, 2010). The roadmap provides an important foundation for this project and this section captures a few key concepts towards summarizing the algal biofuels enterprise.

Algae are efficient factories capable of taking a carbon source such as carbon dioxide and converting it into a high density form of energy (i.e., natural oil). The natural oil must then be extracted and processed to yield a biofuel. Figure 1 shows the spectrum of fuels that can be derived from algae. The microalgae-to-biodiesel pathway is the most developed and holds the greatest potential for near-term commercialization; thus, it is the focus of this study. According to the DOE roadmap, algal feedstocks have unique advantages for the production of advanced biofuels:

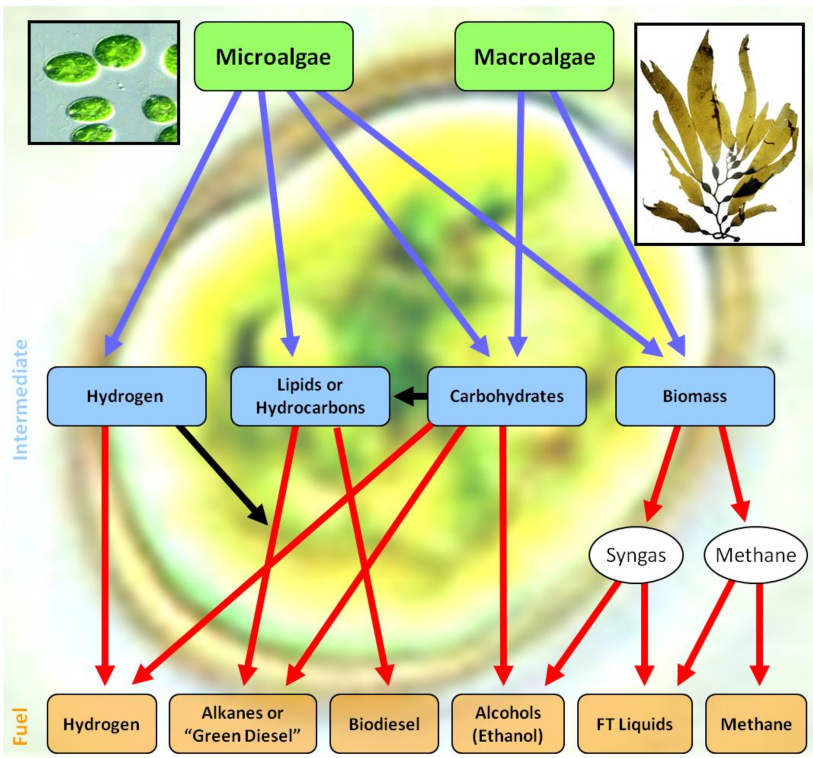

Figure 1. Potential Biofuels Portfolio Using Algae as a Feedstock: Routes to Biofuels Starting With Algae. This Study Focuses on Microalgae Which Have the Capacity to Produce Lipids That Can be Converted to Biodiesel—From Stanley Bull (MRIGlobal)

- Algae cultivation features high area productivity.
- Algae production minimizes competition with conventional agriculture.
- Algae can utilize water from a wide variety of sources, including water of compromised quality.
- Algae can be used to recycle emissions of carbon dioxide from stationary sources such as electric utility power plants.
- Algae production is compatible with the integrated production of fuels and co-products within biorefineries.

The main steps in algal biofuels production include: algae feedstock selection; algae cultivation; algae harvesting, dewatering, and extraction; and conversion of the extracted algal intermediates to biofuels and possibly other co-products. These steps and the key siting and resource elements are depicted in Figure 2. Each of these steps has an established foundation but technology innovations are needed to make production viable at the commercial scale. Various types of systems have been proposed to cultivate microalgae (Table 1). Photoautotrophic systems use light and carbon dioxide to grow algal biomass. A portion of the biomass is lipid which can be converted to biofuels. Assessments have been conducted for both photobioreactors and open-pond raceways systems. Heterotrophic systems grow algal biomass without light, using a carbon source such as sugar to grow biomass by fermentation. At this time there is no clear favorite but the open-pond raceway configuration seems to be getting the most attention form demonstration and commercialization perspective. Once grown, the algae must be harvested and dewatered. Approaches to harvesting and dewatering include flocculation and sedimentation, flocculation and dissolved air flotation, filtration, and centrifugation. Additional drying may be necessary. These processes are equipment and energy intensive. Subsequently, the lipids (and other intermediates) must be extracted from the cell. Solvent-based extraction is assisted by microwaves or sonication to rupture the cells. Other extraction approaches are being investigated. Next the algal extracts are converted to fuels. These processes necessarily depend on the type(s) of fuels to be produced. In particular, lipids can be converted to biodiesel using chemical transesterification or biochemical, enzymatic conversion. *Algal biofuels production is a multi-step process that requires numerous raw materials and energy. This presents both a challenge to economic viability of commercial scale processes but also the economic activity through not only fuels sales but also the substantial investment in capital equipment, supplies and services*.

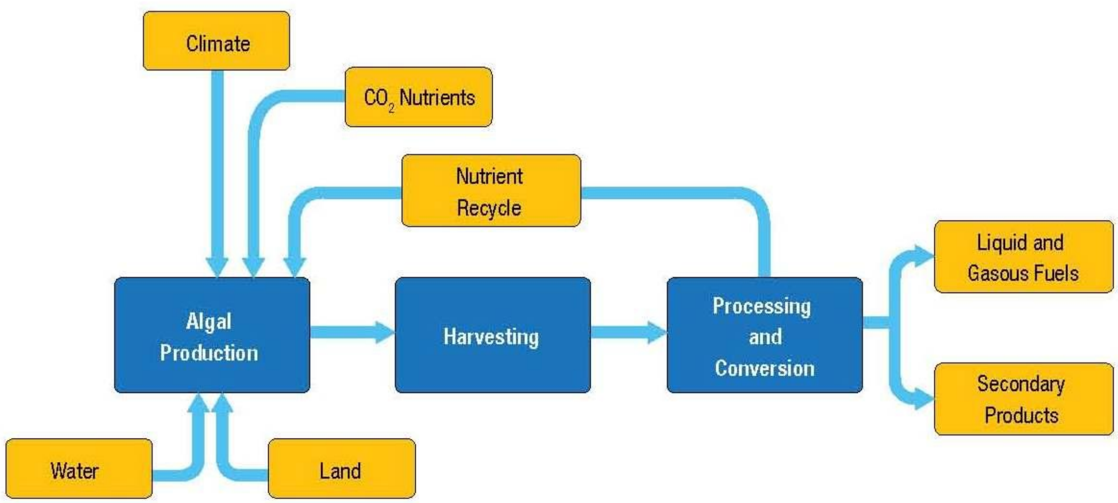

Figure 2. Key Siting and Resource Elements in Algal Biofuel Production—From U.S. DOE (2010)

Table 1. Cultivation Approaches for Microalgae Production—From U.S. DOE (2010)

		Advantages	Challenges
Photoautotrophic Cultivation	Closed Photobioreactors	• Less loss of water than open ponds • Superior long-term culture maintenance • Higher surface to volume ratio can support higher volumetric cell densities	• Scalability problems • Require temperature maintenance as they do not have evaporative cooling • May require periodic cleaning due to biofilm formation • Need maximum light exposure
	Open Ponds	• Evaporative cooling maintains temperature • Lower capital costs	• Subject to daily and seasonal changes in temperature and humidity • Inherently difficult to maintain monocultures • Need maximum light exposure
Heterotrophic Cultivation		• Easier to maintain optimal conditions for production and contamination prevention • Opportunity to utilize inexpensive lignocellulosic sugars for growth • Achieves high biomass concentrations	• Cost and availability of suitable feedstocks such as lignocellulosic sugars • Competes for feedstocks with other biofuel technologies

Section 2. Biofuels in the Context of U.S. and Missouri Energy Portfolios

This section provides two perspectives on the case for biofuels in general and biodiesel in particular. One perspective is the role of biofuels in a comprehensive renewable energy portfolio. The other perspective is the role of biofuels as a replacement for petroleum towards implementing the renewable energy portfolio and providing a more secure supply of transportation fuel.

2.1 Biofuels and the Expanding Renewable Energy Portfolio

Figure 3 shows domestic energy flows for 2009. Virtually none of the energy supply is stored, and thus production (including imports) translates directly to consumption within the four end use sectors—residential, commercial, industrial, and transportation. Renewable energy accounted for 8 percent of the overall U.S. energy supply. Petroleum (domestic crude oil and imported petroleum) was responsible for 35 percent of the overall U.S. energy supply with about 30 percent from domestic production and 70 percent from imported oil.

Recent trends in domestic consumption of energy from renewable sources are shown in Figure 4. Over the past 6 years domestic consumption of renewable energy has increased by 29 percent and in 2009, accounted for 8 percent of total energy consumption. Biofuels energy consumption was 3.1 times higher in 2009 compared to 2004; only wind energy consumption increased at a higher rate (4.9 times higher). In 2009 biofuels energy consumption was still 2.2 times higher than wind energy consumption and accounted for 1.6 percent of all domestic energy consumption and 20 percent of renewable energy consumption. *Biofuels are an important segment of the nation's renewable energy portfolio and biofuels consumption has been increasing at a rate much higher than the overall renewable energy portfolio*.

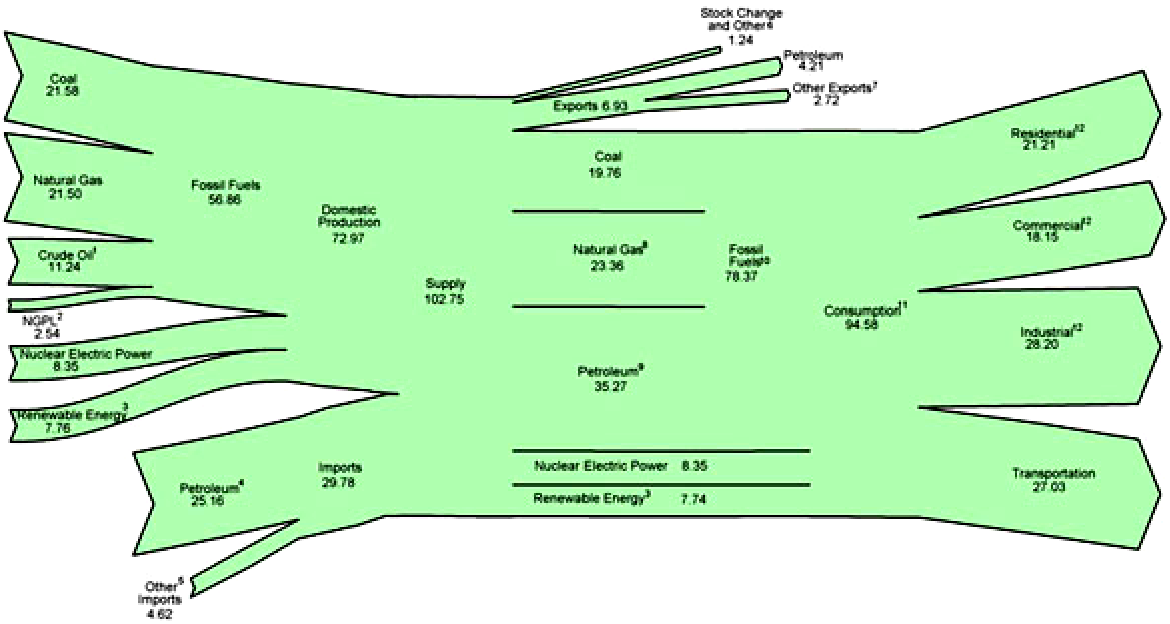

Figure 3. U.S. Domestic Energy Flows for 2009, in Quadrillion Btu—From U.S. EIA (2010a)

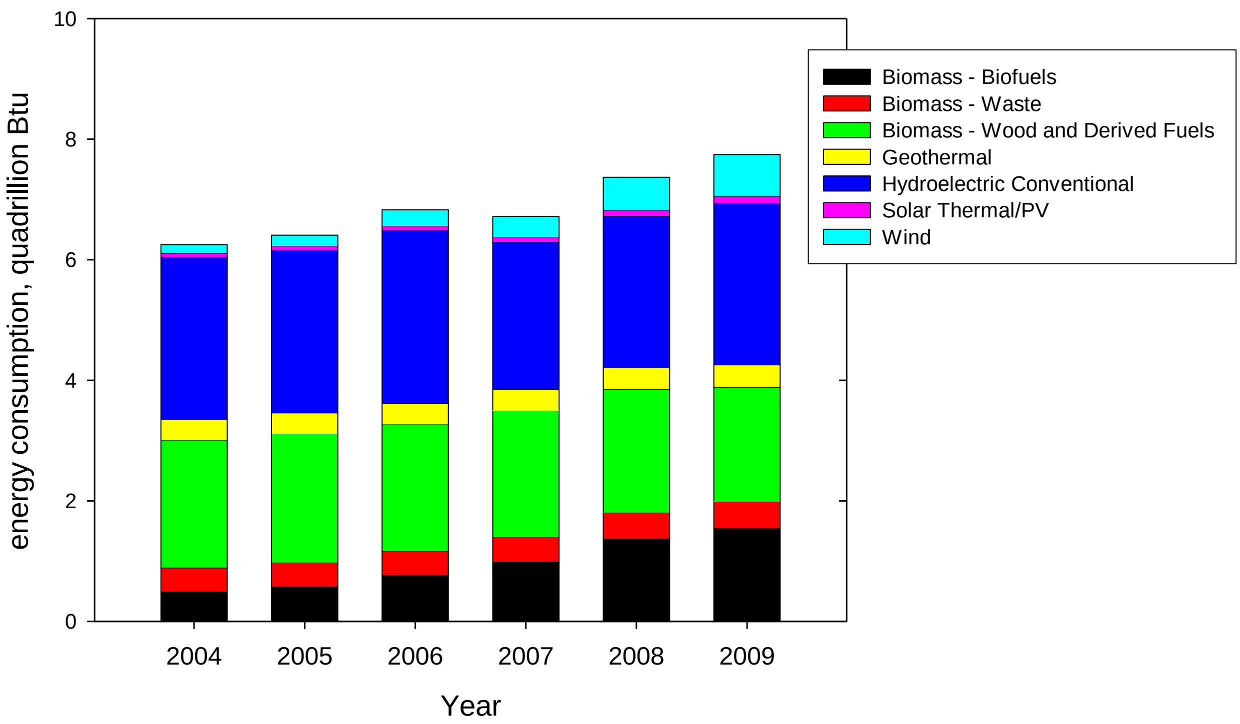

Figure 4. U.S. Annual Energy Consumption From Renewable Energy Sources, 2004 to 2009

Data for 2009 are preliminary. “Biomass—Waste” includes waste landfill gas, municipal solid waste biogenic, and other biomass—Data from U.S. EIA (2010c)

While overall biofuels consumption markedly increased over the 2004 to 2009 period, the trends are different for the two key biofuels—ethanol (which is blended into motor gasoline) and biodiesel. Focusing on these two biofuels which represent virtually all of the biofuels market, Figure 5 shows that ethanol production has steadily increased over the past 6 years—3.7 times higher in 2010 compared to 2004—and accounted for 98 percent of biofuels production in 2008. Annual domestic consumption very closely tracked production. The historical picture for biodiesel is more complicated. Biodiesel production reached a maximum of 7 percent of overall biofuels production in 2007, and in past 2 years has decreased in both relative and absolute terms. Figure 6 more clearly shows the temporal trends for biodiesel production which steadily increased over the period 2004 to 2008 but has subsequently decreased. This trend is consistent with the timing of federal biodiesel tax credits that started in 2005 and expired in 2009, and the timing of a tariff on biodiesel U.S. exports to European Union (EU) countries.

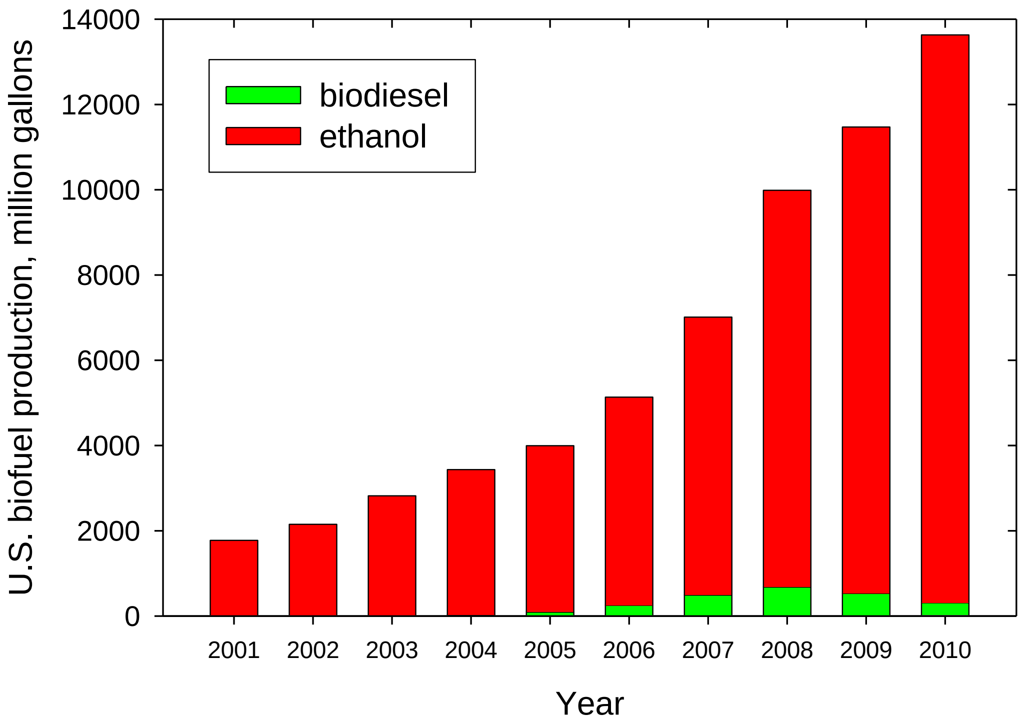

Figure 5. U.S. Annual Production of Biofuels (Top of Bar), 2001 to 2010, Stratified by Biodiesel (Green) and Ethanol (Red)—Data From U.S. EIA (2010a, Updated April 18, 2011)

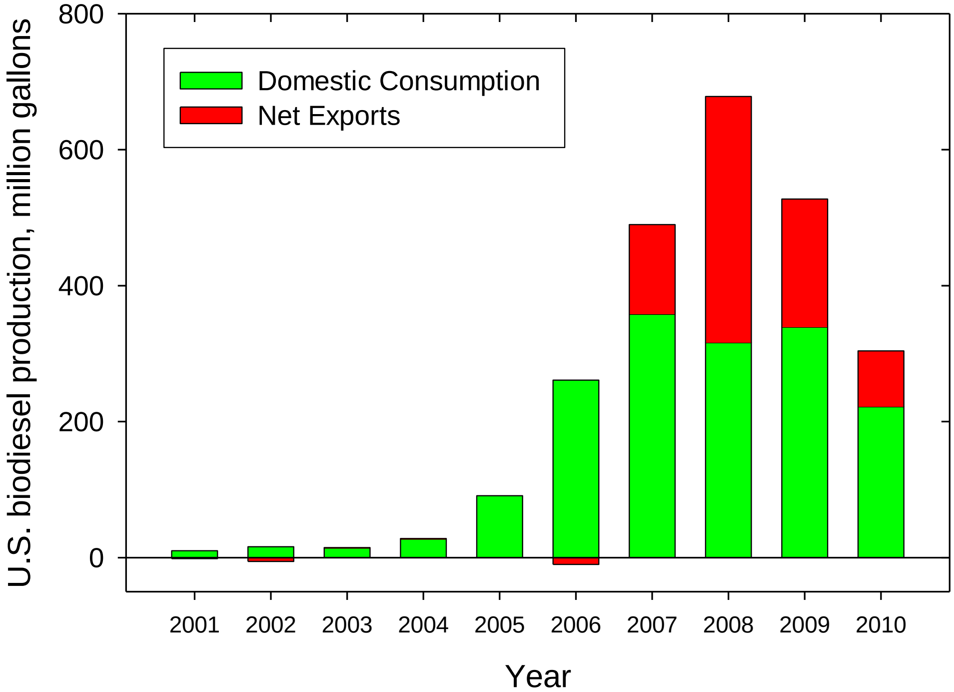

Figure 6. U.S. Annual Production of Biodiesel (Top of Bar), 2001 to 2010, Stratified by Domestic Consumption (Green) and Net Exports (Red)—Data From U.S. EIA (2010a, Updated April 18, 2011)

In 2010, net exports and stock change were only 0.3 percent of ethanol production, whereas for biodiesel net exports were 26 percent of total production (and 53 percent in 2008). The drivers for these trends need to be examined in more details to better understand the market structure of biodiesel from the perspective of an industrial sector that could contribute to the national and state economies and as a source of energy towards meeting national and state energy demands.

2.2 Biofuels and the Nation's Dependence on Imported Oil

Figure 1 is somewhat misleading because it suggests that any energy source can be coupled with any end use. In practice, there is strong coupling between the type of energy source and its end use sector as shown in Figure 7. This profoundly influences how specific renewable energy sources affect the energy supply portfolio for each end use sector with most renewable energy platforms used for electricity generation or direct thermal heating applications rather than transportation fuels. While the relative flows can adjust to some extent to changes in supply, demand, and technological innovations (such as the development of electric vehicles), both the existing infrastructure and logistical issues will certainly constrain such changes over the near term. Biofuels are overwhelming used as a replacement for petroleum. Figure 8 shows the 2009 domestic energy flows for petroleum. Consumption was dominated by the transportation (71 percent) sector and industrial sector (22 percent).

Within the transportation sector 94 percent of the energy demand is provided by petroleum. Alternative transportation fuels such as compressed and liquefied natural gas, electricity, and hydrogen will likely continue to gain market penetration over the next few years but these technologies affect the motor vehicle gasoline market, and thus the operating space for ethanol, whereas in the U.S. the motor vehicle diesel market, which in 2008 accounted for 24 percent of all vehicle fuels consumed, is largely separate and in the near term will not be strongly influenced by competing vehicle technologies that can use the alternative fuels. *From a fuels consumption perspective, the portion of the motor vehicle fleet relying on diesel fuel is unlikely to change in the near term and biodiesel is currently the only viable alternative to petroleum diesel for powering this fleet*. It is projected that over the next two decades domestic refineries will shift their product slate to increase diesel output in response to increased demand for diesel fuel, relatively constant demand for motor gasoline, and decreased refinery capacity (EIA, 2010b). However, this will not profoundly affect the growing market for biodiesel.

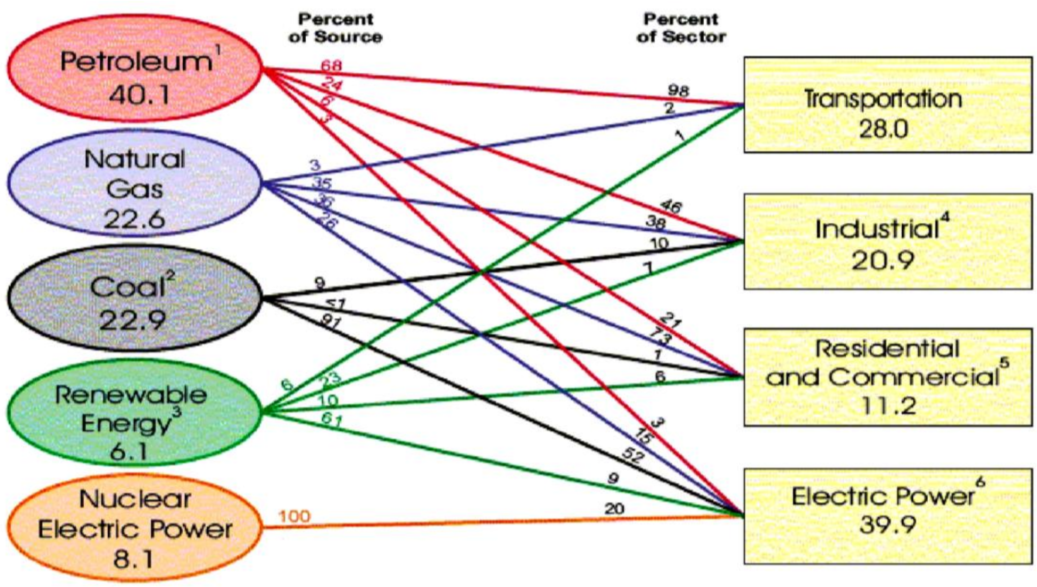

Figure 7. U.S. Domestic Energy Flows by Supply Source and End Use Sectors
All Values Are Percentages

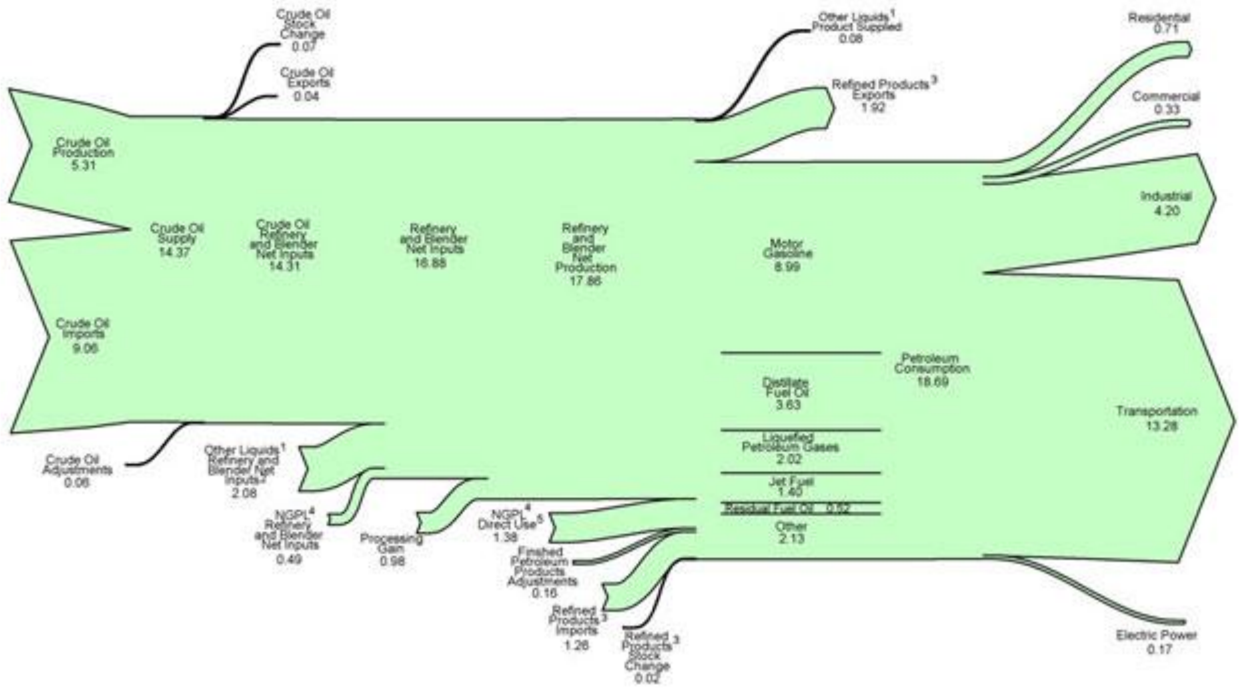

Figure 8. U.S. Domestic Energy Flows of Petroleum for 2009, in Quadrillion Btu—From U.S. EIA (2010a)

Given this background, we summarize the market space for biofuels including biodiesel within the state of Missouri by focusing on transportation fuel use. Both consumption and expenditures are considered because the former more clearly defines the operating space for biodiesel to contribute to Missouri's energy portfolio while the latter directly provides an economic perspective. Figure 9 shows the nearly 20-year trend for transportation fuels consumption in Missouri. Consumption for transportation fuels overall and for distillate fuel oil (diesel for transportation applications) steadily increased throughout most of the 1990s and has been relatively constant for the past 10 years. Transportation fuel expenditures, Figure 10, generally tracked consumption throughout the 1990s with annual average transportation fuel unit costs in the range 7 to 9 million Btu. However, over the past decade expenditures have dramatically increased while consumption has been relatively constant. Average transportation fuel unit costs were 2.3 times greater in 2008 compared to 2000, whereas the consumer price index (CPI) increased by 25 percent.

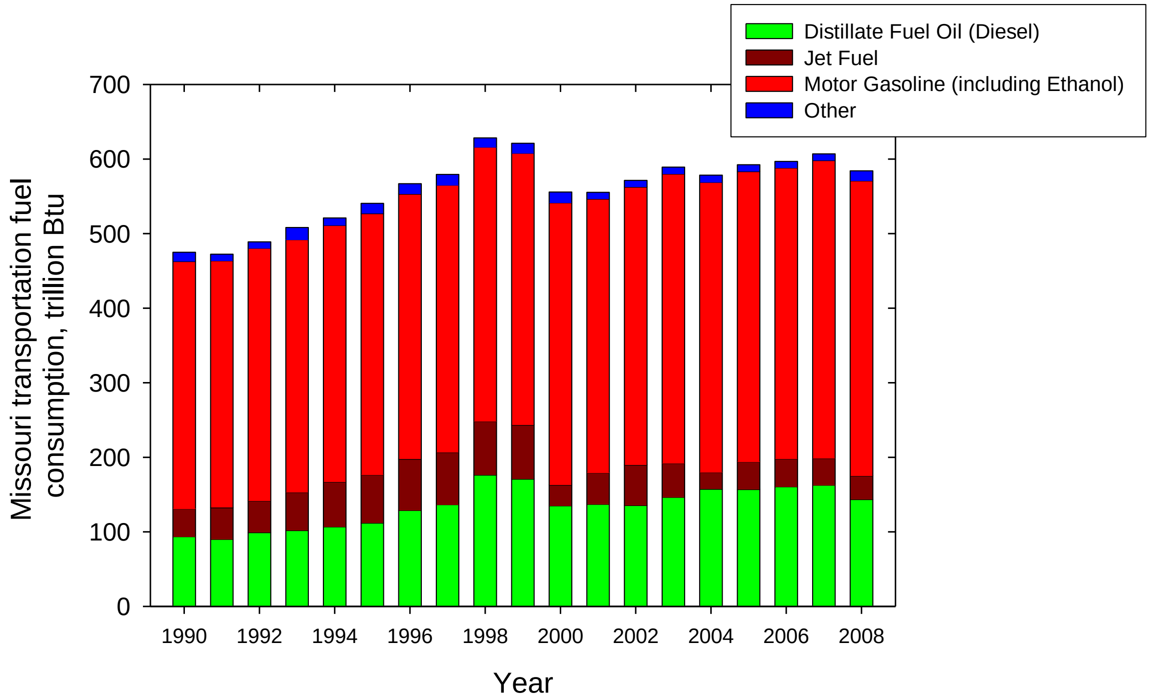

Figure 9. Missouri Annual Consumption of Transportation Fuels (Top of Bar) in Trillion Btu, 1990-2008, Stratified by Fuel Type—Data From U.S. EIA (2010d) [*NOTE: 2009 Data Will be Available in June 2011*]

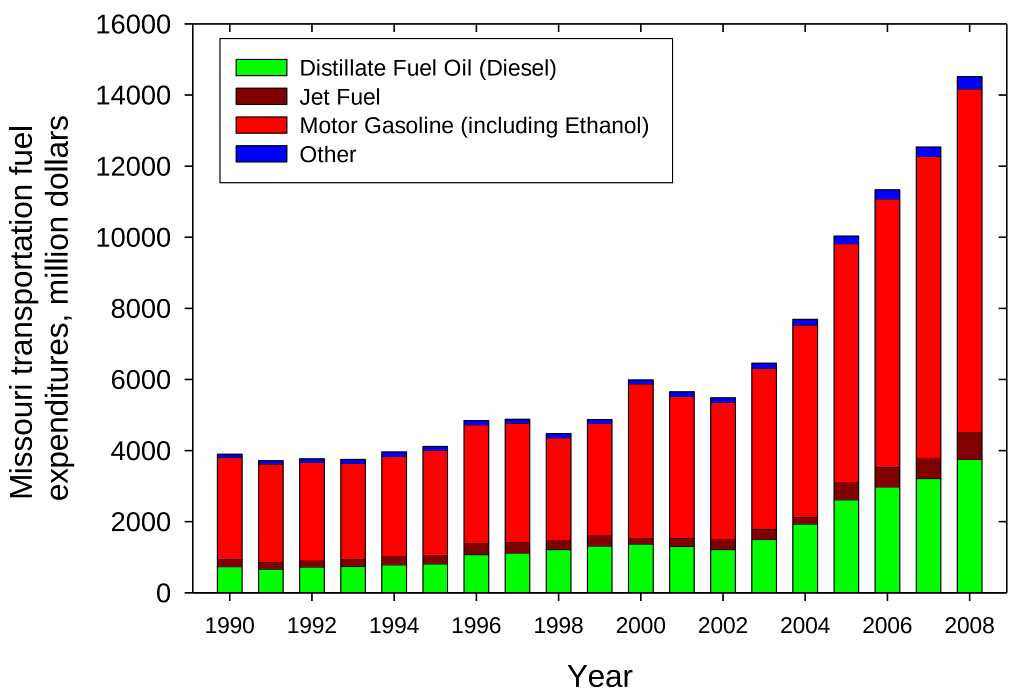

Figure 10. Missouri Annual Transportation Fuels Expenditures (Top of Bar) in Million Dollars, 1990 to 2008, Stratified by Fuel Type—Data From U.S. EIA (2010d) [*NOTE: 2009 Data Will be Available in June 2011*]

Missouri's 2008 expenditures for petroleum was $17.1 billion ($4.6 billion for distillate fuel oil which is primarily diesel but also heating oil). The transportation sector accounted for 80 percent and the industrial sector accounted for 14 percent of Missouri's 2008 total petroleum consumption. Within the transportation sector, petroleum was 99 percent of Missouri's 2008 energy consumption. In both cases distillate fuel oil was about 25 percent of the petroleum consumption. These trends point to the prominent role of petroleum, including diesel fuel, in Missouri's economy, yet there are no petroleum refineries in Missouri. Furthermore, 2008 crude oil production in Missouri was only 99 thousand barrels which was only 2 percent of the state's *fuel ethanol* production. Thus, crude oil production does modestly contribute to the state economy directly; there are contributions through Missouri companies that are suppliers to the production and refining industries out of state. However, the operating space is immense for Missouri to become more self-reliant on transportation fuels by displacing petroleum fuels – with crude oil produced nearly completely out of state and refined entirely out of state—with Missouri-based biofuels and thereby bring economic benefits to the state. Furthermore, the benefits to the Missouri economy through the post-refining distribution and sale of diesel fuel will be present regardless of fuel source. *Increased production of biofuels within the state would represent economic growth rather than displacement from one sector to another*.

Section 3.
The Biofuels Market

3.1 A Midwest Home for Bioethanol and Biodiesel Production

The term biofuels is quite broad. For purposes of this study, “biofuels” include any commodity fuel which is produced using a bio-based feedstock. In practice, this includes fuel ethanol that is blended with petroleum-based motor gasoline and biodiesel as a replacement to petroleum-based diesel. Fuel ethanol can be produced from a variety of feedstocks and in the U.S. it is most commonly produced from corn kernel. Most light duty gasoline vehicles can run on blends containing up to 10 percent ethanol. Engines built for conventional gasoline need major modifications to use fuels with higher concentrations of ethanol. Over the past decade there has been a steady increase in the number of vehicle models that can operate on blends of up to 85 percent ethanol (E85) with more than 70 E85-compatible light duty vehicle models currently on the market and over 9.3 million E85-compatible vehicles in use (NREL, 2010). There are concerns, however, about the sustainability of fuel ethanol derived from the edible portions of plants which can lead to food shortages and increased food prices; however, this is not a universal concern in that some believe recent increases in corn prices are the result of a variety of market forces beyond increased use for fuel ethanol. There is active research into cellulosic ethanol, which is made from the leaves and stalks of corn as well as the cell walls of other plants, and also ethanol from crops that could be grown on land that is unsuitable for food crops.

Biodiesel is diesel fuel made from virgin agricultural products such as vegetable oils and rendered animal fats (tallow) or recycled agricultural oils such as used cooking oils (yellow grease). Biodiesel fuels are direct replacements for the petroleum diesel segment of transportation fuels. Depending on its feedstock it can be used alone or blended with petroleum-based diesel with virtually no changes needed to the engine or its components. Straight run biodiesel tends to have different solvent properties compared to petroleum diesel, yet this is a problem principally on engines manufactured prior to 1992. The U.S. EIA projects nationwide annual biodiesel consumption to reach 43,000 barrels/day by summer 2011 while projected overall distillate fuel consumption (both diesel fuel and heating oil) will average 3.81 million barrels/day. Projected biodiesel production is discussed in more detail below.

Section 2 summarized recent production trends for biofuels in general (Figure 5) and biodiesel in particular (Figure 6). Domestic biodiesel production is quite small compared to the overall market for distillate fuel oil in general and diesel fuel in particular. Soy oil currently is the principal feedstock for biodiesel although other sources exist and processors are trying to expand the types of feedstocks used. The reliance on soy oil for biodiesel and corn for ethanol has led to the Midwest becoming the primary source of bio-based transportation fuels. Transportation of the feedstocks to the processor is a key cost element, so the producers have located near the suppliers. In addition, a number of the processors have been start-ups from farmers’ cooperatives as a means to diversify the markets for their agricultural products, be they soybeans or corn.

The biodiesel industry in Missouri is strong, with eight plants located within the state, including facilities in Dexter, Libourn, Mexico, Moberly, Tina, St. Joseph (2), and Kansas City (NBB, 2011a). Five of the eight facilities use soy oil with the remainder classified as multi-stock. Missouri is also home to the National Biodiesel Board (NBB), a national trade group headquartered in Jefferson City that represents the biodiesel industry. NBB was founded in 1992 by state soybean commodity groups and has a stated goal of replacing 5 percent of domestic diesel demand with biodiesel by 2015.

One relatively new process which could affect Missouri's processing industry is the development of a "green diesel" refining process. Currently, processors use transesterfication to convert the raw oil into diesel; the green diesel process uses more conventional fractional distillation to convert the raw oil to diesel, so green diesel's properties are nearly identical to petroleum-based diesel.

3.2 Federal Tax Policies and Government Mandates

The biofuels market is impacted by the price of oil, government mandates, and incentives such as tax credits. Tax credits are used to achieve energy and environmental policy goals by making biofuels economically competitive with petroleum fuels. The American Jobs Creation Act of 2004 provided the first significant federal excise tax credits for biodiesel (Koplow, 2009) which, together with agricultural subsidies for soybean crops led to favorable economics for soy-based biodiesel production. The Energy Policy Act of 2005 extended the tax credits through 2008 and the Emergency Economic Stabilization Act of 2008 extended the tax credits through 2009. The central element of the multi-faceted biodiesel tax credit program was a $1.00 credit per gallon produced and resulted in $840 million of tax expenditures in fiscal year 2009 (CBO, 2010). These credits expired on December 31, 2009, and, along with a tariff on biodiesel exported to Europe, led to the production decreases shown in Figure 6 because biodiesel was uncompetitive with petroleum-based diesel. Biodiesel production from soybean oil decreased while production from other fats and oils remained largely unchanged (FAPRI, 2010). Total biodiesel production in 2010 was less than half of that in 2008, so on average current production is well below plant capacity. The Tax Relief, Unemployment Insurance Reauthorization, and Job Creation Act of 2010, enacted in December 2010, retroactively extends the biodiesel tax credit through December 31, 2011, and is expected to increase domestic biodiesel production.

In addition to tax credits, mandates are important elements of a comprehensive policy to promote the production and use of biofuels. The Energy Independence and Security Act of 2007 (EISA) set requirements for the minimum use of renewable fuels through 2022. EPA enforces the EISA requirements through the Renewable Fuel Standard (RFS) program (RFS2 as amended to satisfy EISA). EISA includes requirements for the minimum consumption of cellulosic biofuels, biomass-based biofuels, advanced biofuels, and total renewable fuels. The biomass-based diesel fuel requirement reaches 1.0 billion gallons in 2012 with requirements in the out-years to be determined annually by EPA rulemaking based on U.S. EIA estimates and an assessment of domestic production capacity, but shall be no less than 1.0 billion gallons per year. The advanced biofuels requirement started at 0.6 billion gallons in 2009 and increases to 21.0 billion gallons in 2022 (EPA, 2010).

To comply with RFS2, fuel vendors must meet annual blending requirements or purchase credits from other vendors who exceed the blending requirements (CBO, 2010). Biofuels mandates were met each year from 2006 through 2009 but the advanced biofuels mandate—established in 2007 and first effective starting in 2009 and set at 0.6 billion gallons—was not met. Domestic biodiesel was responsible for virtually all of the advanced biofuels produced in 2009 but fell about 0.1 billion gallons short of the mandate. RFS2 standards for 2011, include 0.8 billion gallons of biomass-based diesel which is 17 percent greater than the maximum annual biodiesel production of 678 billion gallons that occurred in 2008. The 2011 RFS2 standard also requires1.35 billion gallons of advanced biofuel; biomass-based diesel consumed in excess of 0.8 billion gallons can be counted towards the advanced biofuels standard (EPA, 2010).

Additional agency-specific policies call for increased use of renewable fuels including but not limited to biofuels. The U.S. Department of Defense (DoD) has been particularly aggressive in this arena. Agency wide, Executive Order 13514 (October 8, 2009) calls for a 30 percent reduction in the consumption of petroleum gasoline and diesel fuel by non-tactical vehicles by 2020. There are also several initiatives specific to the military branches:

Navy

- New requirements for acquisition processes. Mandatory evaluation factors used when awarding contracts for platforms, weapons systems, and buildings will include lifecycle energy costs, fully burdened cost of fuel, and contractor energy footprint.
- Sail the "Great Green Fleet." Demonstrate a Green Strike Group, composed of nuclear vessels and vessels powered by biofuels, in local operations by 2012. By 2016, sail the Green Strike Group as part of a Great Green Fleet, composed of nuclear ships, surface combatants using biofuels with hybrid electric power systems, and aircraft flying on biofuels.
- Reduce petroleum use in non-tactical vehicles. By 2015, the Navy will reduce petroleum use in their commercial fleet by 50 percent using flex-fuel vehicles, hybrid electric vehicles, and neighborhood electric vehicles.
- Increase alternative energy use Navy-wide. By 2020, alternative energy sources will provide 50 percent of total Navy energy consumption.

Air Force

- Increase no-petroleum based fuel use by 10 percent per annum in the motor vehicle fleet. The goal is to increase renewable energy use by 5 percent by FY2010, 7.5 percent by FY2013, and 25 percent by FY2025. Half of the increase must come from new renewable energy sources.
- By 2016, be prepared to acquire 50 percent of the Air Force's domestic aviation fuel requirement via a cost competitive alternative fuel blend. The alternative component of the fuel will be derived from domestic sources produced in a manner that is greener than fuels produced from conventional petroleum.

Army

- Reduce dependence on fossil fuels. Increase the use of clean, renewable energy and improve the efficiency of existing energy systems to reduce their dependency on fossil fuels and to optimize their environmental sustainability.
- Improve energy security. Provide for the security and reliability of energy and water systems in order to provide dependable utility services.

In summary, *federal tax credits for biodiesel production, renewable fuel standard requirements, and agency-specific directives for increasing the use of biofuels including biodiesel all work towards providing a more secure market for biodiesel*.

3.3 Projections for Future Growth

The tax credits, mandates, and other directives summarized above all suggest optimism for an expanding biodiesel market. Indeed, the National Biodiesel Board expects 2011 to be a record year for production (NBB, 2011b). The EPA estimated in late 2010 that total biodiesel production capacity in the U.S. was about 2.4 billion gallons per year (EPA, 2010) so the mandated level can be met with existing capacity with additional room for growth. The aforementioned U.S. EIA projection of nationwide annual biodiesel consumption to reach 43,000 barrels/day by Summer 2011 corresponds to 0.94 billion gallons per year which would meet the RFS2 standard for biomass-based diesel and provide excess consumption to be counted towards the advanced biofuels standard.

Looking father into the future is a more uncertain task. However, the Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri is a leader in such projections. In 2010 FAPRI published a market outlook through 2020. Key assumptions included the $1/gallon tax credit is extended indefinitely and the RFS2 biomass-based diesel mandate is fixed at 1 billion gallons per year after 2012. Figures 11 to 12 show their projections for domestic biodiesel production and domestic biodiesel use, respectively. Their key conclusions include:

- Biodiesel production will increase to satisfy the RFS2 biomass-based diesel requirements and to help meet the RFS2 advanced biofuels requirements.
- In the out-years there will be modest increases in biodiesel exports, despite the EU tariffs, due to increased biodiesel prices in Europe.

3.4 Other Market Factors

Besides excise tax policies, consumption mandates, and agency-specific programs, other factors help to push the growth in biofuels. The price of petroleum was remarkably stable through 2004, but has exhibited dramatic fluctuations since that time. In July 2008, it reached a record high of $145 per barrel before bottoming out at $30 per barrel less than 6 months later.

More recently, the price is once again on the rise due to an improved economy driving demand and concern about geopolitical instability in the Middle East.

Recent price increases and price volatility aside, there are other issues that push the U.S. towards pursuing other energy sources, among them concerns over climate change. While a carbon tax or cap and trade scheme is unlikely in the near future, the EPA is moving forward with attempting to regulate carbon emissions through the Clean Air Act. Furthermore, the EISA renewable fuel standards have greenhouse gas (GHG) thresholds for what fuels qualify for each category such as advanced biofuels.

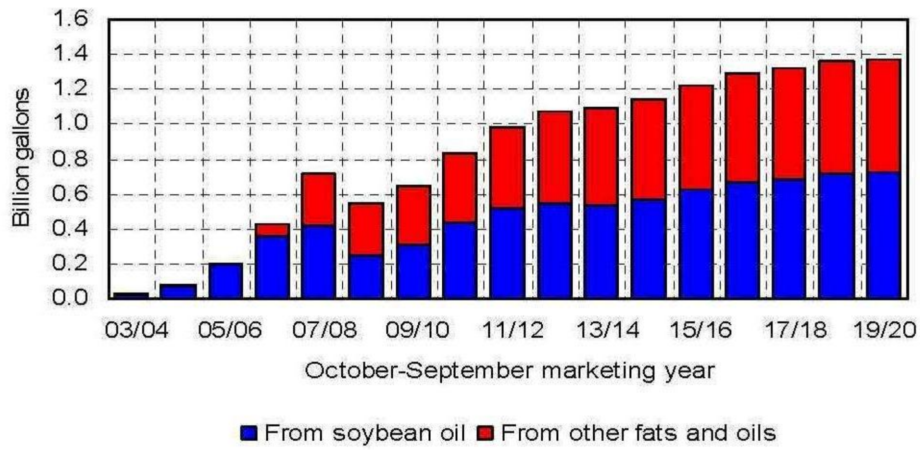

Figure 11. Biodiesel Domestic Production—Recent Trends and Projections Through 2020—From FAPRI (2010)

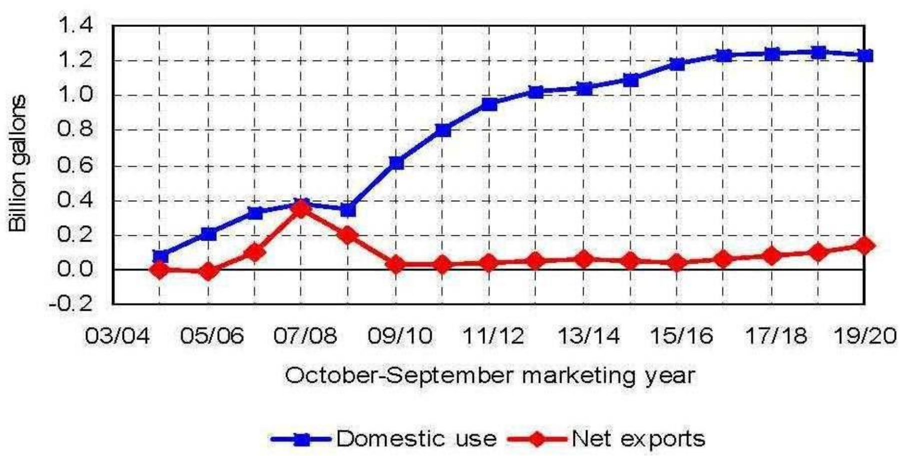

Figure 12. Use of Domestically Produced Biodiesel—Recent Trends and Projections Through 2020—From FAPRI (2010)

3.5 Diversifying the Biodiesel Feedstock Platform

Biofuels are already an important element of the nation's renewable energy portfolio and the tax credits, use mandates, and other policies summarized above are expected to further drive their production and use. Expanded use of domestic biofuels would reduce our dependence on foreign oil. In addition, processing tends to be distributed with biorefineries having smaller capacities than most petroleum refineries. This decentralization makes the fuel production and delivery system less susceptible to supply chain disruptions, such as from natural disasters. For instance, Hurricanes Katrina and Rita in 2005 hit the oil-producing and refining regions of Louisiana and east Texas especially hard, causing significant (albeit temporary) price spikes and shortages.

Biofuels come from a variety of feedstock which gives their production more flexibility should there be poor harvests. In fact, this already occurs with biodiesel where many processors have sought waste oils or other less expensive alternatives to soybean oil due to the loss of the $1 per gallon tax credit.

Biodiesel feedstocks are commonly classified as being first, second, or third generation (Ahmad et al., 2011). First generation feedstocks were the first agricultural crops used for biodiesel production. Examples include soybeans and palm oil. Concerns over the use of edible oils for transportation fuel, and the resulting negative impacts on food supply and prices, drove the development of second generation feedstocks. Examples include agricultural non-food crops such as jatropha and also waste cooking oils, grease, and animal fats. Second generation feedstocks based on agricultural non-food crops avoid the conflict in using edible oils for transportation fuel but they share disadvantages with first generation feedstocks such as relatively low yields and thus high land area requirements. Third generation feedstocks are derived from microalgae (coined "algaculture" in contrast to agriculture). As briefly stated in Section 1.1 and expended in the next section, there are numerous advantages to algal biodiesel production. While agricultural crops—both food and non-food—cannot sustainably displace a large fraction of petroleum transportation fuels, there is relatively widespread belief that algae has the potential to do so (Ahmad et al., 2011). Table 2 provides productivity and land use metrics for a variety of biodisel sources for the scenario of obtaining 50 percent of the current U.S. transportation fuel demand from biodiesel (Christi, 2007). Microalgae, at the relatively conservative estimate of 30 percent oil by weight in the biomass, beats all of the first and second generation agricultural crops listed.

Table 2. Comparison of Some Sources of Biodiesel, Including Land Area Required to 50% of the U.S. Transportation Fuel Demand—Adapted From Christi (2007)

Feedstock	Oil yield ($L\ ha^{-1}yr^{-1}$)	Required land area (M ha)	Percentage of U.S. cropping area
First generation			
Corn	172	1,540	846
Soybean	446	594	326
Canola	1,190	223	122
Coconut	2,689	99	54
Oil Palm	5,950	45	24
Second generation			
Jatropha	1,892	140	77
Third generation			
Microalgae[1]	58,700	4.5	2.5

[1] Assumes 30% oil by weight in biomass.

Section 4.
Algal Biofuels Production: Current Status and Future Prospects

The previous sections suggest an expanding market for biofuels including biodiesel. Microalgae are receiving much attention as a platform for making an array of biofuels with biodiesel being the best near-term prospect. Algal biofuel production has not yet been realized on a commercial scale but relatively large investments are currently being made to address the barriers to commercial viability. Several companies around the world are developing algal-based processes for biofuel production and other purposes. These companies, which are mostly located in the U.S., have been summarized by Singh and Gu (2010) and will be described in more detail in the Task B and Task C reports. There has also been a dramatic increase in published assessments—including in the peer reviewed literature—of various aspects of algal biofuel production at scale including land, water, and energy demands and environmental impacts such greenhouse gas emissions (Lardon et al., 2009; Smith et al., 2009; Batan et al., 2010; Clarens et al., 2010; Stephenson, et al., 2010; Cooney et al., 2011; Wigmosta et al., 2011). Some of these assessments focus strictly on the algal biofuel production processes only while others take a lifecycle (cradle-to-pump) approach. The recent trend of publishing both technology and impact assessments is promising and more-detailed, transparent economic analyses are also beginning to emerge.

Several recent summaries present a relatively optimistic view of the prospects for algal biofuel commercialization both domestically and abroad (Christi, 2007, 2008; Khan et al., 2009; Singh and Gu, 2010; Ahmad et al., 2011; Demirbas and Demirbas, 2011; Tabatabaei et al., 2011). One source states that "it is foreseen by the U.S. industry that full commercialization of algae oil will begin to take place in the U.S. in roughly 4 to 5 years [from 2010]" (Singh and Gu, 2010). However, much work is needed to make algal biofuel production a viable sustainable industry. DOE's algal technology roadmap, developed in 2010, is presented on Figure 12. The map shows the many factors involved in the production and processing of algae to produce biodiesel and other products. Besides siting and resource issues, appropriate species must be chosen and a host of engineering-related functions must be optimized, including harvesting, dewatering and extraction. While many of the siting and resource issues will be affected by site-specific conditions such as geography and local climate, and thus not all areas are suitable for growing algae, there are myriad opportunities to develop the industries needed to support the algal biofuels enterprise such as providing equipment, supplies, and research expertise.

As a global commodity, biofuels must compete against petroleum. Developing, demonstrating, commercializing and gaining market penetration is an economic challenge for any emerging fuel technology and the development of biofuels has been only possible through tax subsidies and other government policies. If algae production can include the development of high value, "niche" products (such as specialty food additives) the return on these products could provide revenue that improves the economics of producing algal biofuels. Indeed, the commercial viability of algal biodiesel production might well hinge on adopting a biorefinery based production strategy (Singh and Gu, 2010). In principle, all of the algal biomass that is harvested can be processed into useful products and detailed summaries of the spectrum of products have been presented (Spolaore et al., 2006; Christi, 2007; Harun et al., 2010; Mata et al., 2010; Singh and Gu, 2010). In addition to biodiesel from the lipids content, other algal cell components could be used to produce a biocrude feedstock for the production of other liquid chemicals (Figure 1). Indeed, the non-lipid components of algae could be used to produce a variety of products including bioethanol (by fermentation of the carbohydrates and proteins), animal and fish feed, livestock protein additives, organic fertilizer, pharmaceutical products, health oils (such as omega 3) and biogas such as biomethane. High-value, low-volume co-products, such as the health oils and pharmaceuticals, may prove to be key to the near-term economic feasibility of algal biofuel production. At very large biofuel production scales, however, the markets for co-products might be constrained and technological advances in both the biology and downstream processing are needed to improve the prospects for commercial viability (Cooney et al., 2011).

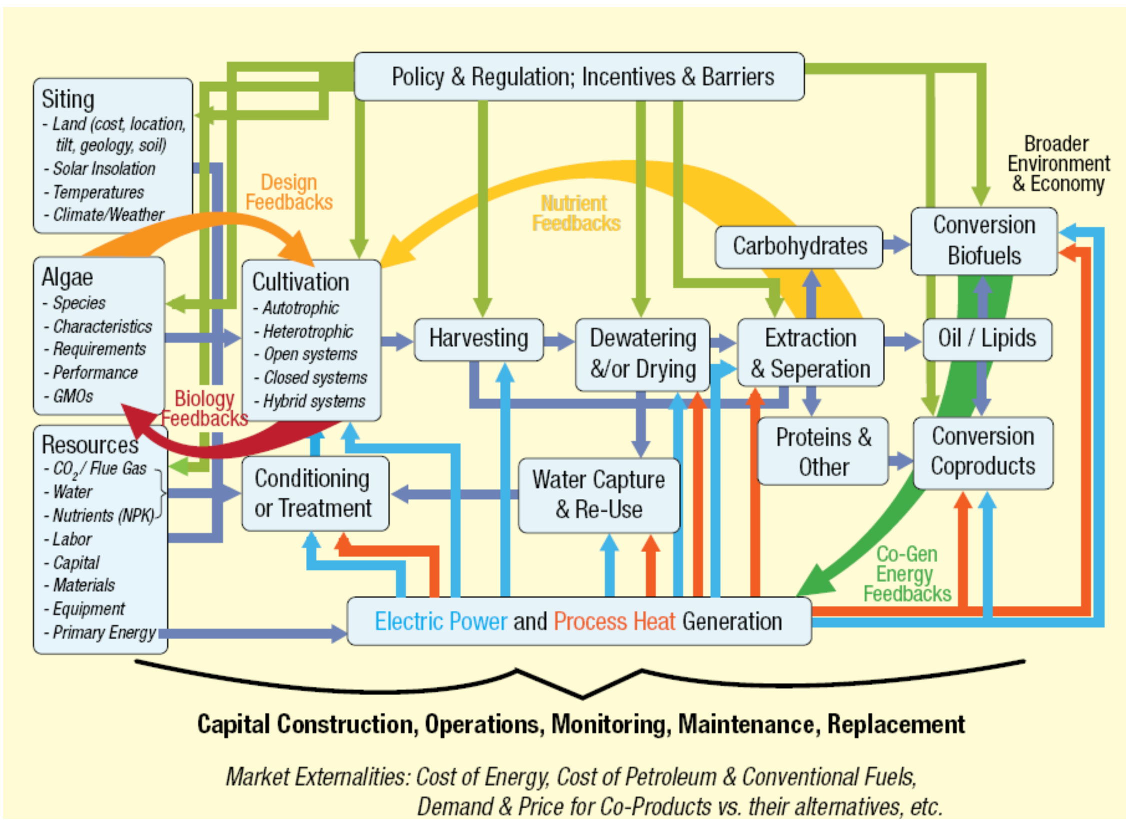

Figure 13. Algal Biofuel Production and DOE's Technology Roadmap—From U.S. DOE (2010)

The biofuels industry in general, and biodiesel from microalgae in particular, holds significant promise. It is technically feasible but advances are needed in both the biology and downstream processing to make it commercially viable. These challenges will be detailed in the Task E report. While technological hurdles exist, there are significant parallels with other types of industrial processing to warrant some optimism. Large research efforts are underway—including in Missouri—to advance the technologies for the growing, harvesting and processing of microalgae.

Section 5.
Missouri's Assets for the Algal Biofuels Industry

This study aims to determine what specific attributes Missouri has that would be beneficial in promoting the development of an algal biofuels industry within the state. A myriad of economic, environmental and geopolitical forces are fueling interest in alternative transportation fuels, and algal biofuel is being considered as an approach to provide a portion of the world's future energy mix. Microalgae offer certain advantages over other biofuels and thus have been receiving considerable attention. Missouri's assets for algal biofuel production, for providing manufacturing and other services supporting the algal biofuel production enterprise, and serving as a hub for research and development will be identified and inventoried in Task B and critically compared to other regions in Task C. This section highlights some key considerations.

5.1 Algal Biofuels Production

Figure 12 demonstrates there are several siting and resource considerations that influence the economic viability of algal biofuel production. These assets vary by location and therefore influence the competitive advantage of certain geographic regions. Screening studies can be conducted to identify geographic areas that are potentially favorable for algal biofuels production. Subsequently, detailed site-specific studies are needed that comprehensively assess all of the factors that affect economic viability. One recent screening study considered land use and water requirements to evaluate the viability of algal production at high spatial resolution nationwide (Wigmosta et al., 2011). From the land suitability perspective the criteria included the land be relatively flat with adequate open fetch, and that it be "nonagricultural, underdeveloped or low-density developed, nonsensitive, and generally uncompetitive land." An open pond algae growth model was used to estimate spatially resolved theoretical biofuel production yields and water requirements. Locations along the Gulf Coast were deemed most favorable. Missouri fared poorly in this assessment (e.g., Figure 13 which shows annual biofuel production under current technology at each of the modeled ponds) because the potentially prime locations within the state for algal biofuel production are already croplands in cultivation and therefore failed the initial screening criteria and were removed from further consideration. While there is reluctance to endorse the widespread replacement of food cropland with non-food energy crops, *strategic conversion* of cropland should be considered. Thus, an assessment is needed with the land use criterion relaxed to gain insights into Missouri's likelihood of competitive advantage for algal biofuel production. The Missouri Bootheel, for instance, is characterized by flat lands, abundant water, and a warm and humid climate. The region's location adjacent to the Mississippi River is especially advantageous, given that the floodplain characteristic of the region has water very near the ground surface. Similarly, Missouri is bisected by the Missouri River and its floodplain, which is characterized by abundant amounts of water and the flat lands of the river bottoms. There is abundant water and several cities are located along its banks which could be potential nutrient sources from municipal wastewater systems. Further, there are several opportunities to co-locate algae production facilities near existing electric utility power plants which could provide both a carbon dioxide source and waste heat needed to extend the growing season through Missouri's cold winters. Task E will explore these considerations in more detail.

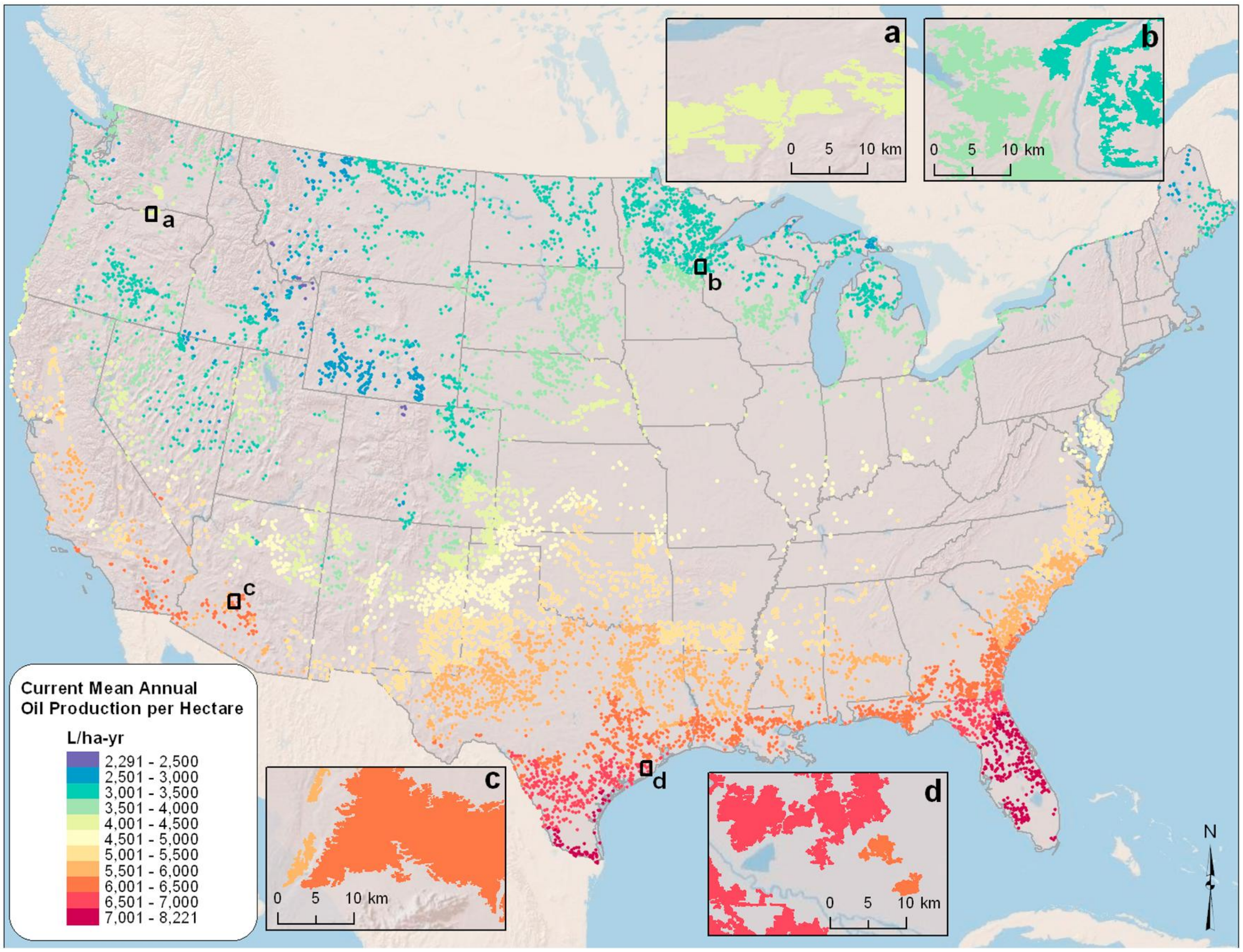

Figure 14. Mean Annual Biofuel Production (L ha^{-1} yr^{-1}) Under Current Technology Plotted at the Centroid of Each Modeled Hypothetical Pond—From Wigmosta et al. (2011)

5.2 Equipment Manufacturing and Services Supporting Algal Biofuels Production

Beyond climate and resource characteristics that might make algal biofuel production attractive within the state, Missouri also has substantial industrial resources. For example, the Missouri Department of Economic Development recently evaluated Missouri's industrial machine manufacturing industry, which covers a wide variety of manufacturers exporting their equipment outside the state. The industry includes over 580 different establishments with average wages of more than $42,000 per year, developing a variety of machinery including mining equipment, tractors, lawn mowers, waste disposers, industrial molds, scales, freezers and furnaces. Existing establishments are concentrated in eight areas, including St. Louis metro, St. Joseph, Columbia, Ava, Sedalia north to Slater, Camdenton and Hannibal (Missouri DED, 2011). An industrial base exist which could support the need to design and manufacture equipment used in the production and processing of algae. Task D will focus on the opportunities for Missouri to be a leader in supplying products and services to the algal biofuels industry.

5.3 Research and Development Hub

The St. Louis region is a major center for biotechnology research, specifically as pertains to agricultural research. The Donald Danforth Plant Science Center (DDPSC), Monsanto, and Washington University in St. Louis (WUSTL) lead a cluster of world-class plant research activities that continue to spin off new companies. These institutions are collectively an excellent resource that could act much like the famous Route 128 high-tech corridor in Boston that uses their research institutions as a resource. Two DOE Energy Frontier Research Centers (EFRC) are based in St. Louis—the Center for Advanced Biofuel Systems (DDPSC) and the Photosynthetic Antenna research Center (WUSTL). DDPSC is the Consortium Team Lead for the National Alliance for Advanced Biofuels and Bioproducts (NAABB) which is a DOE Algal Biofuels Research Consortium. Other research specific to algal biofuels production is currently underway in the state at the University of Missouri-Columbia, Missouri University of Science and Technology in Rolla, and at MRIGlobal.

Future tasks will more comprehensively identify and document specific assets within the state that could support and benefit from an algal biofuels industry. The research and industrial assets will be examined in Task B, and those assets will be compared to other states in Task C. Subsequent tasks will identify potential markets and explore the many technical and financial challenges. These efforts will be used to evaluate policy initiatives and opportunities for Missouri in the algal biofuels industry.

Section 6.
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